THE DEPENDENCE OF SIDE IMPACT INJURY RISK ON MDB CONFIGURATION

Mark Terrell, Craig Newland, Keith Seyer

Department of Transport and Regional Services, Australia

Dainius Dalmotas

Transport Canada

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ABSTRACT

This paper reports on a parametric study of side impact crash tests. Relative changes in injury risk are assessed for both front and rear struck side occupants in tests with variation of mass, stiffness, geometry and speed of the impacting mobile deformable barrier.

The study concludes that the ground clearance of the MDB face and impact velocity have a significantly greater effect on injury risk than the other parameters.

The paper also includes consideration of tests to further investigate the effects of mass ratio between the struck and striking vehicle.

This cooperative project between the Australian Department of Transport and Regional Services and Transport Canada includes analysis of intruding door behaviour and consequent effects on injury risk.

INTRODUCTION

In the development of vehicle standards to provide improved protection in side impact crashes there has been considerable debate surrounding the relative importance of the various parameters of impact configuration. The two existing crash regulations, ECE Regulation 95 and US FMVSS 214 employ similar principles with a moving deformable barrier striking a stationary vehicle, however the barrier and trolley configuration differ considerably.

The intent of this study is to provide a quantitative assessment of the effect of variations in trolley mass, element stiffness and geometry, and speed. While this study concentrates on one target vehicle type, a large Australian passenger car, a second vehicle type was included to support consideration of mass variation.

This parametric study varies characteristics of the impacting trolley and assesses the effect on vehicle side structure and dummy responses.

The results of this series of tests are being used in the development of a harmonised test procedure to improve protection in a wide range of side impact crashes.

METHOD

A single vehicle model was used, with dummy responses being measured with variation in parameters of the striking trolley:

- Mass
- Deformable element stiffness
- Deformable element stiffness distribution
- Ground clearance of deformable element
- Angle of impact (crabbed or perpendicular)
- Impact Speed

Target Vehicle

The chosen target vehicle was the Ford Falcon EL model, a typical large Australian passenger sedan. This model is structurally the same as the previous EF model, which was used in previous tests conducted by DoTRS[1]. The vehicle was claimed by the manufacturers to comply with the requirements of US FMVSS 214, which was confirmed in the earlier DoTRS test series.

With the exception of test 9, where target vehicle mass was varied, all target vehicles in the main test series had a test mass of 1765kg. Identical dummies, instrumentation and camera set-up were used for all tests. The mass variation for test 9 was achieved by removing the engine and drivetrain, most engine bay components, non-struck side doors and other parts that were considered not to affect the test outcome.

The springs were modified to maintain the same ride height as the heavier target vehicle.

Vehicle Instrumentation

Table 1 lists the accelerations recorded on the target vehicles:

Table 1.
Vehicle Instrumentation

Lower B-Pillar	Right (struck)	A_X, A_Y, A_Z
	Left	A_X, A_Y, A_Z
Upper B-Pillar	Right	A_X, A_Y, A_Z
	Left	A_Y
Mid B-Pillar	Right	A_Y
A-Pillar	Right	A_Y
C-Pillar	Right	A_Y
Trans. Tunnel		A_Y
Driver Door	Front	A_Y
	Rear Upper	A_Y
	Rear Mid	A_Y
	Rear Lower	A_Y
Driver Seat	Lower Frame	A_Y

The accelerometers placed on the struck side of the vehicle were used to calculate the contact velocity of the side structure to occupants in the vehicle. Driver door accelerometers were mounted to the inner door structure, underneath the door trim panel. Limited mounting space required the use of uniaxial accelerometers only. Accelerometers at the rear of the driver door were approximately aligned with the dummy thorax and pelvis. Relative velocity of door to dummy was calculated by integration of the acceleration. Contact switch signals were used to determine contact time and hence contact velocity. It is recognised that there may be some error in the calculated velocity of the door relative to the dummy due to rotation of the door structure. However, analysis of the deformed vehicles showed that the accelerometer mounting points on the deformed door structure remain close to vertical, therefore the degree of error from rotation is expected to be fairly small. In addition the consistency of the static deformations from test to test is such that comparative assessments can be made.

Dummies

There are a number of side impact dummies currently in use or under development for compliance and research testing. The dummies used for this test series were considered to be the most biofidelic available [2]. A 50%ile BioSID dummy was used in the driver seating position (front outboard struck side) and a 5%ile female SID-IIs (β+) in the rear outboard struck side seating position. The SID-IIs was chosen as a surrogate for an adolescent child, though the results would also be applicable for a small-statured adult female.

Table 2.
Dummy Instrumentation

Head	C of G	A_X, A_Y, A_Z
Upper Neck		F_X, F_Y, F_Z M_X, M_Y, M_Z
Upper Spine (T1)		A_X, A_Y, A_Z
Shoulder		F_X, F_Y, F_Z A_Y,S_Y
Thorax	Upper Rib	A_Y,S_Y
	Middle Rib	A_Y,A_X**,S_Y
	Lower Rib	A_Y,S_Y
Abdomen	Upper Rib	A_Y,A_X**,S_Y
	Lower Rib	A_Y,S_Y
Opposite Thorax	Upper Rib	A_Y
Opposite Abdomen	Upper Rib (T12)	A_X,A_Y,A_Z
Pelvis		A_X,A_Y,A_Z
Iliac		F_Y
Pubic		F_Y
Sacrum		F_Y*

* BioSID only; ** SID IIs only

Contact Switches

Digital contact switches, constructed using horn-switch membranes were located at points on the occupants and in the occupant compartment to enable analysis of the timing of crash events. These were used in the determination of contact velocities. Switches were as described in **Table 3**:

Table 3.
Contact Switch Locations

Driver Dummy	Pelvis	Struck Side
	Upper Arm	Struck Side
Driver Seat	Bolster	Struck Side
		Non-struck Side
Rear Passenger Dummy	Femur	Struck Side
	Upper Arm	Struck Side
	Knee	Struck Side

Data Collection

All test data were collected at a 20kHz sampling rate. Tests were recorded by 8 high speed film cameras including three on-board the target car and one on the impacting trolley. The target vehicle was marked with a 100x100mm grid and points digitised in 3 dimensions in the vehicle's coordinate system before and after the test. Similar measurements on a 100x50mm grid were taken of the barrier element.

Barrier Elements

Four types of deformable aluminium honeycomb elements were used to vary the parameters of stiffness and stiffness distribution. Elements meeting the specification for ECE R95 and FMVSS 214 were used. The ECE R95 element was chosen as a reference and two custom elements based on ECE R95 were manufactured with modified stiffness and stiffness distribution. With the exception of the FMVSS 214 element, all deformable elements used in this test series were supplied by AFL Honeycomb Structures and were manufactured using a chemical etching process.

Baseline (ECE R95) – Element properties as specified in the ECE R95 test procedure.

Type 1 - A custom element design with each block having a nominal stiffness of twice the ECE R95 barrier face. Dimensions were the same as the ECE R95 face.

Type 2 - A second custom element, designed to represent a Sports Utility Vehicle, was also manufactured. Compared to the ECE R95 barrier face, this element had an increased stiffness and modified stiffness distribution with an enlarged centre lower (engine) block of high stiffness.

All elements were mounted using a perforated backing frame to allow venting of the honeycomb in accordance with the manufacturer's specifications.

Details including certification test results for the custom elements can be found in a previous paper documenting this test series [3].

Test Matrix

Table 4 provides a summary of the test matrix used in the parametric study.

The test matrix was designed to independently vary each parameter such that a comparison of two tests would yield information about the effect of a single parameter.

The baseline Test 1 was based on the Economic Commission for Europe (ECE) Regulation 95. A trolley conforming to ECE R95 was fitted with an AFL "Progress" etched aluminium honeycomb element.

Test 2 was the same as Test 1 except the barrier ground clearance was raised from 300 mm to 400 mm.

Test 3 was conducted as a repeat of Test 1 as a result of data acquisition failures for the rear dummy and also provided some repeatability assurance for the driver dummy.

Table 4.
Test Matrix

Test Number	1	2	3	4	5	6	7	8	9	10
Mass of target car										
1765 kg	●	●	●	●	●	●	●	●		●
1045 kg									●	
Impact configuration										
Perpendicular	●	●	●	●	●		●	●	●	
Crabbed						●				●
Mass of MDB										
950kg	●	●	●	●				●		
1365kg					●	●	●		●	●
Type of Element										
AFL Progress ECE R95	●	●	●		●	●		●	●	
FMVSS 214										●
Other				#1			#2			
Barrier ground clearance										
280mm										●
300mm	●		●	●	●	●		●	●	
400mm		●					●			
MDB Speed										
50 km/h	●	●	●	●	●		●		●	
56 km/h @27°						●				●
60 km/h								●		

Test 4 was the same as Test 1 except for the barrier element, which was a custom manufactured element (Type 1) with each block of the element having double the stiffness of the standard R95 element.

Test 5 was the same as Test 1 except that the trolley mass was increased from 950 kg to 1365 kg.

Test 6 was the same as Test 5 except that a crabbed trolley (as defined in FMVSS 214) was used. The barrier element and targeting were the same as for Test 5.

Test 7 was the same as Test 1 except for the following changes to the trolley that were aimed at mimicking a small Sports Utility Vehicle (SUV):

- Mass was 1365 kg
- Barrier face ground clearance was 400 mm
- Custom element (Type 2) with modified stiffness and stiffness distribution.

Test 8 was the same as Test 1 except the impact speed was raised from 50 km/h to 60 km/h.

Test 9 was the same as Test 5 except that the target vehicle mass was reduced to 1045 kg, ie the impacting trolley was heavier than the struck vehicle.

Test 10 was the same as Test 6 except that the barrier face and targeting were in accordance with US Federal Motor Vehicle Safety Standard (FMVSS) 214 ie:

- Trolley mass was 1365 kg
- Trolley crabbed at 27°
- Element ground clearance of 280mm
- FMVSS 214 element (Homogeneous stiffness)

Additional Test

In consideration of the effect of mass it was suggested that the MDB to vehicle mass ratio had a more significant effect on injury measures than impacting mass alone. Test 9, with a reduced target vehicle mass, introduced a number of uncertainties with the unknown effect of changes in mass distribution and rotational inertia of the struck vehicle.

An additional test was conducted using a small European passenger car with a test mass of 1009kg This allowed the use of an impacting trolley with a mass of 1365kg to achieve an MDB to vehicle mass ratio of 1.35. The results from this test were compared to manufacturer's results from an otherwise identical test using a 950kg MDB (MDB to vehicle mass ratio of 0.94).

In order to use the available baseline result it was necessary to test using a EuroSID 1 dummy (driver only), whereas the original test matrix used BioSID driver and SIDIIs struck side rear passenger. It is recognised that this introduces a further variation in test configuration, but this was considered reasonable for the purpose.

RESULTS

Vehicle Responses

Table 5 lists the responses recorded on the target vehicles. Figure 1 shows selected vehicle static intrusion profiles, measured on the outer body panels at the height of the driver H-point.

Table 5.
Vehicle Accelerations

Test Number	1	2	3	4	5	6	7	8	9	10
Peak Acceleration (CFC 60)										
Right B-Pillar (g)	107	115	141	152	85	83	131	125	144	184
@ time (ms)	13.3	30.8	23.4	9.5	14.5	30.0	23.2	11.9	26.7	11.1
Trans. Tunnel (g)	20.9	15.5	23.6	20.5	36.8	17.4	17.9	22.3	19.0	16.8
@ time (ms)	45.3	50.0	37.8	39.4	48.2	26.0	62.1	41.8	47.5	31.4
Left B-Pillar (g)	14.8	12.1	15.6	16.2	26.7	13.5	13.7	14.7	16.8	18.6
@time (ms)	26.6	11.3	26.1	24.9	23.9	74.2	10.9	26.7	46.1	26.2

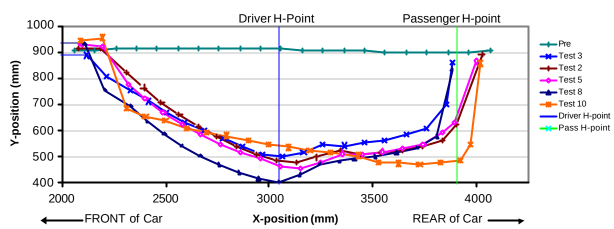

Figure 1 - Static Intrusion profiles

Dummy Responses

Table 6 shows the time and velocity of contact for the driver dummy and the contact times for the passenger dummy. No velocity information was recorded for the passenger door.

Table 6.
Contact Time and Velocity

Test Number	1	2	3	4	5	6	7	8	9	10
Driver Dummy										
Time of closure [ms]										
Shoulder	23.8	18.9	22.1	20.3	25.3	25.9	18.6	19.3	21.2	22.8
Pelvis	26.6	24.5	25.9	22.1	27.2	29.4	23.0	*	26.4	24.0
Door to Dummy Contact Velocity [m/s]										
Shoulder	8.4	10.3	9.2	9.4	8.8	5.7	12.1	9.3	9.5	10.4
Pelvis	7.2	9.2	7.1	6.8	6.1	5.1	8.2	*	7.6	10.7
Passenger Dummy										
Time of closure [ms]										
Knee	31.0	28.7	30.2	24.7	31.3	34.3	23.4	26.2	28.4	21.5
Pelvis	33.8	35.5	32.4	25.9	35.7	39.3	25.4	28.0	32.0	18.3
Shoulder	32.1	28.6	23.7	33.5	34.7	37.0	29.0	30.4	33.4	25.0

* Contact switch failure. Driver pelvis closure time and contact velocity unavailable for Test 8.

In test 1 a number of channels were not recorded for the passenger dummy. These included rib and pelvis accelerations. The baseline ECE R95 test was therefore repeated (test 3).

There were consistent measurement problems with the LVDT transducers measuring rib deflections in the SID-IIs. For a number of tests no values were obtained for either ribs 1 or 2. There were also 'spikes' in the data of several ribs in most tests. This did not generally affect the peak deflection, however the Viscous Criterion algorithm, which uses the differential of deflection to obtain rib velocity, produced unrealistic peaks (resulting from differentiation of the data 'spikes'). Therefore an alternate method of VC calculation was used for the SID-IIs, with rib velocity being calculated by integration of the acceleration of each rib relative to the spine. This produced results which were more realistic. This could not be done for test 1, therefore VC results are not included for this test.

Table 7 shows the measured dummy responses. The shaded cells show the relationship between dummy response and IARVs. It is not the intent of this paper to comment on biofidelity or reference values for the chosen dummies – however where accepted indicative values are available these do provide some guidance as to the important parametric effects. Green shaded cells are well below the IARV. Cells that are shaded yellow are within ± 20% of the IARV and cells shaded orange are well above the IARV.

Table 7.
Dummy injury responses

Driver (BioSID)										
	1	2	3	4	5	6	7	8	9	10
HIC15	137	266	134	278	252	19	416	491	232	46
3ms Head Accel [g]	44	55	42	58	55	18	60	94	52	25
Chest VC [m/s]	0.64	1.33	0.58	0.58	0.65	0.14	1.41	1.48	1.50	0.45
Chest defl [mm]	29.6	58.1	33.4	30.9	36.8	21.2	56.9	48.8	52.2	29.1
TTI [d]	93	127	104	113	97.9	43	122	150	128	81.4
Ab VC [m/s]	0.87	1.15	0.81	0.93	0.91	0.4	1.37	1.0	1.13	0.78
Ab defl [mm]	50	54.2	45.3	51.6	44.3	35.3	62.2	41.9	49.6	45.3
Pelvis Accel (g)	96	91	100	112	109	25.4	105	160	106	86
Pub. F [kN]	5	2.9	4.5	4.9	6.5	0.4	5.2	6.6	3.24	2.2
Passenger (SID-IIs)										
HIC15	49	28	58	80	114	138	157	169	391	221
3ms Head Accel [g]	20	21	29	34	40	48	48	49	80	52
Chest VC [m/s]	*	0.17	0.25	0.3	0.34	0.21	0.58	0.44	0.68	0.79
Chest defl [mm]	25.3	21.9	22.7	30.2	23.1	23.1	28.4	26.8	33.4	35.9
TTI [d]	*	48.9	49.1	46.4	56.1	46	73.6	63.9	74.7	90.2
Ab VC [m/s]	*	0.61	0.63	0.57	0.8	0.41	0.67	0.78	0.92	1.07
Ab defl [mm]	31.8	31.2	33.3	38.3	38.9	32.4	28.8	36.7	44.2	38.1
Pelvis Accel (g)	*	69.1	55.1	63.3	*	41	89	77.3	75.6	140
Pub. F [kN]	0.61	0.54	0.66	0.65	0.70	0.29	0.88	0.91	0.91	1.00

* Instrumentation failure

Further detailed results for the driver dummy can be found in the previous paper [3].

Additional Test

Table 8 shows the EuroSID-1 injury measures for the baseline test (950kg trolley) and the test with an increased mass trolley (1365kg).

Table 8

Dummy responses - additional test

	950 kg MDB (A1)	1365 kg MDB (A2)
Head Accel (3ms) (g)	48.4	78.6
HPC	222	404
Rib1 deflection	38.3	36.2
Rib2 deflection	38	36.7
Rib3 deflection	27.9	32.5
Rib1 VC	0.57	0.59
Rib2 VC	0.62	0.76
Rib3 VC	0.37	0.47
Peak Ab Force	2.01	1.96
Pubic Force	4.22	3.85

Figure 2 shows the relative change in injury responses for the two trolley mass configurations, normalised with respect to the ECE R95 injury limits.

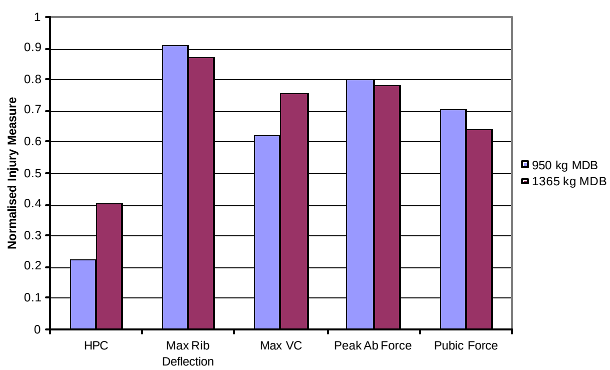

Figure 2 - EuroSID injury responses

DISCUSSION

In the following discussion, injury risk and other metrics are compared with those recorded in Test 1 & 3 which were based on the standard ECE R95 test procedure and used as the baseline. Where results for the passenger dummy were not available from Test 1 the Test 3 results only are used for comparison.

Tests 1 & 3 show a variation of approximately 10% when comparing injury outcomes for these two identical tests. Therefore it is assumed that any change to the injury outcome of less than 10% is unable to be regarded as significant as it is indistinguishable from test-to-test variation.

In Test 6, the etched ECE R95 deformable element was used on a crabbed trolley. During the test, the element failed in shear, producing negligible vehicle deformation and dummy readings that were significantly below the baseline tests for all measures on the driver dummy.

The values for the passenger in Test 6 were below the baseline tests for most measures other than head injury. However, the injury risk was not significant in either the baseline tests or Test 6.

Tests 5 and 6 were designed to assess the effect of crab angle, as this was the only trolley parameter varied between these two tests. Due to the dramatic change in behaviour of the deformable element under shear load, a comparison of these tests does not provide a true indication of the effect of crabbing, particularly with reference to the rear dummy. The results of Test 6 are therefore not discussed further. It is intended to further investigate the effect of crabbing by repeating this test with an element that is stable in shear and / or a test in the FMVSS 214 configuration with a non-crabbed trolley.

The figures in Appendix 1 show the relative change in a range of vehicle and injury measures, in comparison to the baseline tests (1 and 3). The values shown are calculated as:

$$\frac{\text{Test Value} - \text{Average Baseline Value}}{\text{Average Baseline Value}}$$

This provides a graphical representation of the relative results of each test configuration compared to the baseline tests.

Contact Velocity and Timing

An examination of the contact times and door to dummy impact velocities for the driver dummy shows that the shoulder was always struck before the pelvis (i.e. the pelvis lags the shoulder).

An increase in the pelvic lag coupled with an increase in contact velocity results in increased risk of thoracic injury as can be seen in Tests 2, 7 and 9.

By contrast, a decrease in pelvic lag coupled with an increase in contact velocity results in increased risk of injury in only the pelvic region as evidenced by Tests 4 and 10.

This relationship is not seen for the rear passenger dummy, where the kinematics are quite different, with the knee generally being contacted before the thorax or pelvis.

Increased Ground Clearance

Test 2 was the same as Test 1 except the barrier ground clearance was raised from 300 mm to 400 mm. This increase in height is such that the barrier no longer engages the sill of the target vehicle. This resulted in an increase in both the shoulder and pelvis contact velocities for the driver dummy, as well as an increase in the pelvic lag. The results indicate that the upper door area was contacting the dummy 5.6 ms earlier than the lower door contacting the pelvis. When compared to Tests 1 & 3, the higher intrusion profile is clearly seen to affect the thoracic loading of the driver dummy with the chest VC and deflection doubling. The injury measures for the pelvic area remained static. These results suggest that the high thoracic loading is caused by the high degree of pelvic lag.

The increased barrier ground clearance did not have a significant affect on the injury measures for the rear dummy when compared to the baseline tests.

Increased Stiffness

Test 4 used a Type 1 modified deformable barrier face (with a nominal stiffness twice that of the ECE R95 barrier face). Compared to Tests 1 and 3, Test 4 showed a slight increase in shoulder contact velocity for the driver dummy, but a slight reduction in pelvis contact velocity and a reduction in pelvic lag, resulting in increased injury risk for the head and pelvic region. Abdominal and thoracic injuries remained unchanged.

The increased stiffness produced a slight increase in most injury measures for the passenger dummy. The most significant increase was in thorax rib deflection, which was approaching the IARV of 34mm.

Effect of Mass

Test 5 was the same as Test 1 except that the trolley mass was increased from 950 kg to 1365 kg. The shoulder contact velocity was the same as for the baseline tests and the pelvis contact velocity decreased slightly. In addition, the pelvic lag was reduced. With the exception of pubic force, head and pelvic g's, this test caused no significant increase in injury risk.

There was a slight increase for most injury measures for the rear dummy, however all but the abdomen deflection were below the injury reference values.

The increased trolley mass in Test 5 did produce an increase in the peak acceleration of the vehicle, measured both at the left B-pillar and the transmission tunnel. This was not observed in other tests such as test 7, where the trolley mass was also 1365kg. This is likely because Test 7 also has a raised element with minimal sill engagement, therefore the additional energy may have been used in intrusion rather than acceleration of the target vehicle.

Test 5 used a 1365kg MDB to impact the 1765kg target vehicle, whereas the baseline tests used a 950kg MDB. In both cases the struck vehicle mass was significantly greater than the MDB mass resulting in an MDB to target vehicle mass ratio of les than 1 as shown in Table 9.

It was considered infeasible to conduct a test using an MDB with a mass greater than 1765kg. In an attempt to conduct a test with an MDB to target vehicle mass ratio greater than 1.0, an EL Falcon target vehicle was prepared with the test mass reduced to 1045kg. This was achieved by removal of driveline components and mass from the non-struck side of the vehicle. No mass was removed from the impacted structure of the vehicle.

The chest and abdominal injury measures for the driver dummy in Test 9 were similar to Test 8 and amongst the highest recorded. However, the pelvic responses were similar to the baseline. This is in contrast to Test 5, where the increased trolley mass produced thorax and abdomen injuries similar to the baseline, with some increase in pelvic load, particularly pubic force. It is noted that Test 9 had the 2^{nd} highest amount of pelvic lag (5.2 ms).

Passenger dummy responses were also high for this test. A head contact was recorded and there was also a significant increase in thorax VC. Other measures showed a consistent increase over the baseline.

By removing the driveline components to reduce the mass of the target vehicle in Test 9 it is expected that the centre of gravity would be increased relative to the ground. It is unknown what effect this has on the kinematics of the target vehicle. Analysis of the high speed film indicates this vehicle rolls more than the other target vehicles.

The additional test (A2) was included in comparison with the manufacturer's data (A1) to provide further understanding of the effect of mass ratio change on dummy responses. This achieved an MDB to target vehicle mass ratio of 1.35, but without the removal of large amounts of mass from the struck vehicle. As shown in Figure 2, there was a slight increase in injury risk for some body regions (head and thorax VC) but these were not significant in magnitude and all measures remained below the regulatory limits. It is notable that a head contact to the door beltline was observed with the increased trolley mass that did not occur with the 950kg trolley.

The results from this test support the observations of Test 5 that increased trolley mass has only a slight effect on dummy responses.

Table 9
Vehicle / Bullet Mass Comparison

Test	1	5	9	A1	A2.
Target Mass [kg]	1765	1765	1045	1009	1009
Bullet Mass [kg]	950	1365	1365	950	1365
Mass Ratio Bullet / Target	0.54	0.77	1.31	0.94	1.35

Crab Angle

Test 6 was the same as Test 5, but used a crabbed (27°) trolley with a chemically etched ECE R95 barrier. Unfortunately the front (etched) section of this element failed in shear and therefore this test does not provide any further information for this parametric study.

Compound Variation

Test 7 was based on Test 1 but aimed at mimicking a small Sports Utility Vehicle (SUV) by using a trolley mass of 1365 kg, ground clearance of 400 mm and a custom deformable element (Type 2). For the driver dummy this configuration greatly increased the door to dummy shoulder contact velocity as well as increasing the pelvis contact velocity and pelvic lag. This resulted in greatly increased injury risk in both the thoracic and abdominal areas. There was also an increase in head injury risk.

Test 7 combined the heavy mass and increased ground clearance coupled with a modified stiffness and stiffness distribution. Compared to Tests 2, 4 and 5, Test 7 produced the highest driver dummy shoulder contact velocity, but Test 2 produced the highest pelvis contact velocity and largest pelvic lag. The driver thoracic injuries for Tests 2 and 7 were similar, and approximately twice that for the baseline tests.

This suggests that for the driver thorax, increasing the barrier face ground clearance has a very large effect on injury risk, whilst mass and stiffness have only a minor effect. In the abdomen, Test 7 showed the highest injury risk of all tests, with Test 2 showing the second highest. This further supports the notion that ground clearance is the predominant factor of all the compound variations in Test 7 and that mass, stiffness and stiffness distribution are less significant. In the pelvic region, Tests 4 and 5 showed a more significant influence on sacrum, iliac and pubic force than Tests 2 or 7. However, these increases in injury risk were all moderate and pelvic acceleration and TTI[d] were similar for Tests 2, 4, 5 and 7. This indicates that mass and stiffness may have a moderate influence on injury risk in the pelvic area.

For the passenger dummy the compound variation of Test 7 produced a significant increase in head acceleration (without contact) and chest VC was more than double the baseline value. There were also increases in TTI and pelvis acceleration that were greater than those measured for any of the parametric variations separately. Abdomen responses however remained essentially unchanged from the baseline.

Increase In Test Speed

Test 8 was the same as Tests 1 & 3 except the impact speed was raised from 50 km/h to 60 km/h. In Test 8, the driver pelvis contact switch did not indicate closure until after 70 ms, whereas the dummy’s pelvic acceleration signal clearly showed an impact with a peak at 28.9 ms. In addition, the relative velocity of the door to dummy pelvis changes rapidly from 8 m/s to 4.8 m/s over the time interval from 21 to 23 ms. This further supports the notion that the door contacts the pelvis around that time.

Despite the fact that the closure time and contact velocity at the driver pelvis were unable to be determined, the pelvic acceleration is delayed in time relative to the thoracic acceleration, suggesting that a pelvic lag also occurs with this test. Abdominal rib deflection was the lowest recorded, however, abdominal VC was the fourth highest and almost 20% higher than the baseline test. The pelvic acceleration was the highest recorded while the chest VC was the 2^{nd} highest. Iliac, sacrum and pubic force were also amongst the highest. These highly increased injury risks for the driver dummy were recorded without a correspondingly high increase in door to dummy contact velocity at the shoulder. As the pelvis contact velocity and pelvic lag are unknown for this test, it is not possible to come to a firm conclusion regarding the cause of the high dummy measures recorded. The rear of the driver head also recorded a glancing contact to the B-Pillar.

The passenger dummy also recorded a consistent increase in injury measures, though of slightly lesser order than the driver dummy.

It is useful to note that the kinetic energy of the trolley in Tests 5 and 8 was the same. Both these tests used a trolley with 132 kJ of impact energy (an increase of 44% over the baseline test which had 92 kJ). Test 5 used an increased trolley mass to raise the kinetic energy, whereas Test 8 used an increased impact velocity. The results clearly show that the increased impact velocity produces higher injury risk than the test with the same impact energy using a lower impact speed with higher mass.

Crab Angle and Stiffness Distribution

Test 10 used the same target vehicle conditions as Test 1 however, the trolley configuration, targeting and the deformable element were in accordance with US Federal Motor Vehicle Safety Standard (FMVSS) 214. All injury outcomes for the driver dummy decreased or were similar to the baseline except for sacrum force, which was about 60% higher. High contact velocities were measured at both the shoulder and pelvis, but this test resulted in the smallest pelvic lag of all tests (1.2 ms). This indicates that the shoulder and pelvis were impacted at almost the same time and with the same velocity, spreading the loads across the dummy. Compared to the baseline tests, this vertical intrusion profile produced in Test 10 leads to reduced or unchanged injury risk in all body regions. It is noted that the target vehicle was designed to meet FMVSS 214.

The responses for the passenger dummy however showed a different trend with increases over the baseline tests in all measures. Thorax VC was more than 3 times that of the baseline, with pelvis acceleration more than double. There were also significant increases in head acceleration, TTI and abdomen VC.

The static intrusion profiles shown in Figure 1 show that the FMVSS 214 barrier element has produced significantly greater intrusion at the point of the rear dummy than all other configurations. It is not possible to determine from this series whether this is a result of the element geometry or the crabbed configuration or both. This may be established by a further test, using the FMVSS 214 configuration, but without the crabbed MDB.

SUMMARY

While the results of this parametric study are specific to the subject target vehicle, some further support has been added with the inclusion of results A1 and A2. The results are also in strong agreement with other studies using variation of the impacting object [4],[5].

Driver Dummy

For the driver dummy the two most significant effects on injury risk were increase in element ground clearance and increase in test speed. This can be seen in Test 2, where the increased MDB element height produced a significant increase in mostly thoracic injury, and Test 8 where increased test speed produced increased injury to all body regions.

Increase in MDB mass had only a marginal effect on injury risk for the driver dummy (Test 5 and Test A2). A greater effect was observed when the target vehicle mass was reduced, however it is unclear to what extent this result was affected by changes to kinematics resulting from changes to the vehicle’s moments of inertia and centre of gravity.

Doubling the MDB element stiffness produced an increased driver injury risk only in the pelvic area.

Test 7, using a MDB with increased mass, height and stiffness produced increases to both pelvic and thoracic loading.

Impact to the driver dummy pelvis consistently occurred after impact to the shoulder. The amount of ‘pelvic lag’ and the door contact velocity appears to influence the severity of thoracic loading.

The test using the FMVSS 214 configuration (Test 10) produced driver dummy responses reduced from those of the baseline tests (with the exception of sacrum force).

Passenger Dummy

The trends in results for the rear dummy with parametric variation are generally consistent with those observed for the driver dummy with the following exceptions:

- Pelvis contact does not consistently lag shoulder contact – pelvis contact does not appear to be a good predictor for injury to thorax or other body regions with the most severe tests showing pelvic lead.

- While head contact was observed in only 1 test (Test 9), with a moderate HIC (391) there was a high head acceleration (80g) resulting from contact with the C-pillar.
- Test 10, with the FMVSS 214 configuration, showed high injury measures, including the highest pelvis acceleration and iliac force. This is in contrast to the driver dummy, where this test produced injury measures that were consistently lower than the baseline tests. It is unclear whether this is a result of the crabbed impact configuration or the FMVSS214 barrier element, which is wide with homogeneous stiffness over the complete barrier face. Element aiming may also be a factor.

The measures for the passenger dummy were generally either well below the IARV or borderline. There were only two results that significantly exceeded the IARV. Both of these were for abdominal rib deflection (Tests 5 and 9).

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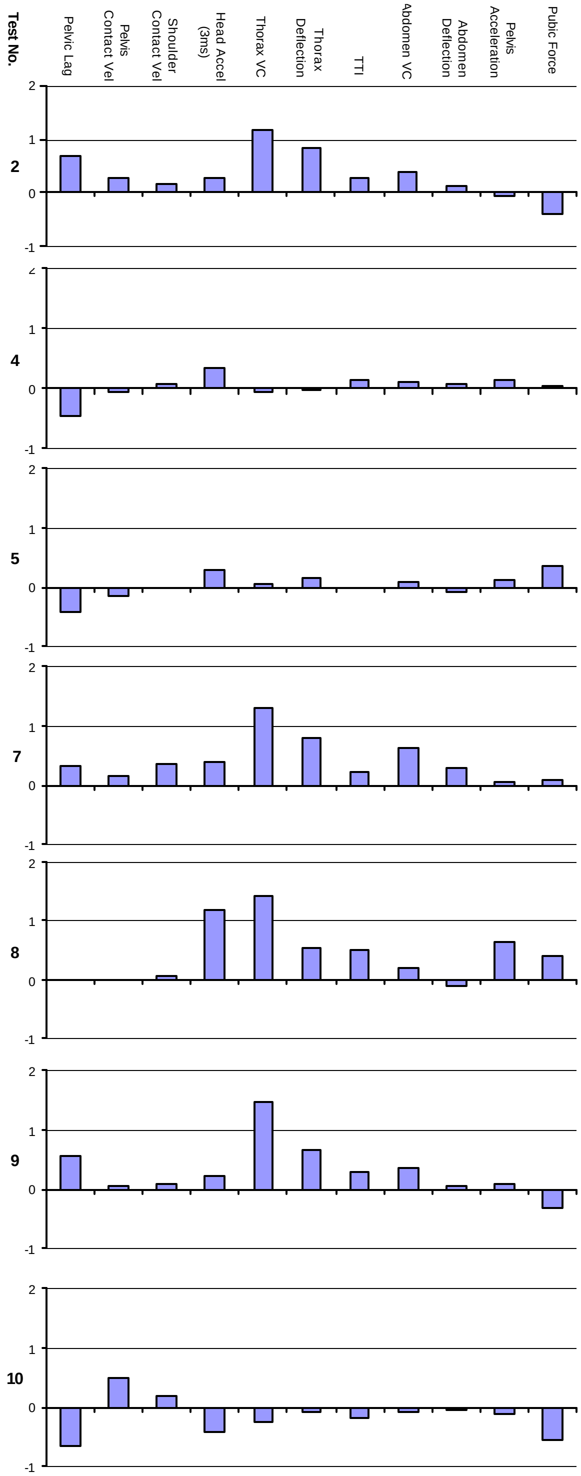
APPENDIX 1

Driver Dummy



Passenger Dummy